REPORT No. 715

LATERAL CONTROL REQUIRED FOR SATISFACTORY FLYING QUALITIES BASED ON FLIGHT TESTS OF NUMEROUS AIRPLANES

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SUMMARY

An analysis has been made of the aileron control characteristics of numerous airplanes tested in flight by the National Advisory Committee for Aeronautics. In the correlation of satisfactory and unsatisfactory characteristics with measured values, it was found that the helix angle pb/2V, which expresses the lateral displacement of the wing tip in a given forward travel of the airplane, was the measure of the aileron effectiveness appreciated by the pilots. It was also found that regardless of size or category of the airplanes tested, which included pursuit, transport, training, and bomber types, a value of pb/2V of 0.07 represented a criterion of minimum satisfactory aileron effectiveness.

By the use of previously developed theory, the observed values of pb/2V for the various wing-aileron arrangements were examined to determine the effective section characteristics of the various aileron types.

INTRODUCTION

A few years ago the National Advisory Committee for Aeronautics instituted a program for the study of airplane flying qualities. The primary purpose of the research program was to determine quantitatively what constitutes satisfactory flying qualities and the stability and the control requirements that an airplane can be expected to fulfill. Accordingly, the investigation has consisted mainly in determining these characteristics in flight tests of various airplanes. These airplanes were made available largely by the Army and more recently by private companies through the cooperation of the Civil Aeronautics Authority.

Stability and control characteristics have now been determined for a large number of airplanes of varied types. The data obtained not only show what constitutes satisfactory flying qualities but also, through analysis, show how various design features influence the observed flying qualities.

In the analysis of these data and in the preparation of reports, it has been convenient to consider separately the various phases of control and stability. Thus, the present report is confined to the results of the analysis of aileron control. In addition to the data obtained in tests performed specifically to determine flying qualities, data obtained in previous lateral-control investigations have been included in the analysis. Although this report deals particularly with characteristics of conventional ailerons, some data on spoiler and floating-tip ailerons were used to aid in formulating the criterion of minimum satisfactory aileron effectiveness. Including alterations to the wings and the ailerons of two of the airplanes tested, a total of 28 different wing-aileron combinations was investigated. The data analyzed cover the range of span, aspect ratio, and taper ratio in current use.

SYMBOLS

The symbols used in this report are as follows:

p rolling velocity, radians per second
V air speed, feet per second
b wing span, feet
$\bar{c}_a$ average chord of aileron back of hinge line
$\bar{c}_b$ average chord of aileron balance
$\bar{c}_{w_a}$ average total chord of that section of the wing covered by an aileron
$\Delta\delta_a$ angular difference between up and down ailerons, degrees
k aileron effectiveness factor, effective change in angle of attack of wing-aileron section per unit aileron deflection, $\Delta\alpha/\Delta\delta$
C_{l_δ} rate of change of rolling-moment coefficient C_l with aileron angle δ
C_{l_p} rate of change of rolling-moment coefficient C_l with helix angle $pb/2V$
C_L lift coefficient
α angle of attack

FLIGHT TESTS

The flight-test procedure for measuring aileron effectiveness consisted in trimming the particular airplane for straight flight at a given air speed and then abruptly applying aileron control, holding the rudder locked. Records were taken of rolling velocity, yawing velocity, air speed, and control position. Aileron control forces were also recorded whenever feasible. This procedure was repeated for various aileron deflections, at various speeds, and for different combinations of flap and power. Standard NACA flight-test instruments were used, the data being recorded photographically and synchronized by means of a timer.

General results for conventional ailerons may be summarized as follows:

(1) The rate of roll for a given airplane at a given control deflection was very nearly a linear function of air speed except for cases where control-cable stretch appreciably limited the available aileron deflections. At a given air speed the rate of roll progressively increased with aileron deflection, the type of variation being dependent on the type of aileron balance. In some instances, with balanced ailerons, a point was reached where further deflection produced no additional rolling moment.

(2) None of the aileron combinations tested exhibited objectionable lag characteristics. Rolling accelerations were great enough in all cases that the rolling velocity furnished the important measure of aileron control from the pilot's viewpoint.

(3) Rates of roll that would have been unsatisfactory for small airplanes were considered entirely adequate for large airplanes.

(4) Rates of roll that were considered inadequate at high speeds were satisfactory at low speeds.

(5) The effectiveness of the aileron control in normal flight had no correlation with the aileron control at the stall. In no case could the completely stalled airplane be controlled by means of the ailerons.

(6) Power or flap position had only very slight effects on the rolling velocities obtained.

(7) Some of the large airplanes tested suffered severely from the effects of control-cable stretch in limiting the available aileron deflections, particularly at high speeds. It would also appear that the large airplanes and some of the small airplanes with fabric-covered wings lost a considerable amount of potential rolling ability through wing warping due to the torsional loads applied by the deflected ailerons.

In the summary of the flight data obtained from the various airplanes tested, it was desirable to use the nondimensional expression $pb/2V$. Interpreted physically, $pb/2V$ represents the lateral displacement of the wing tip in a given forward travel of the airplane or, in other words, the helix angle generated by the wing tip. The characteristics of conventional ailerons are such that, for geometrically similar airplanes regardless of size or air speed, substantially constant values of $pb/2V$ are obtained for a given aileron deflection. Thus, the rolling performance of an airplane may be defined in terms of the numerical value of $pb/2V$ obtained with full control deflection for the case of conventional ailerons that reach full deflection at all speeds under consideration.

This method of presentation has been used in table I where the characteristics of the various airplanes tested have been tabulated. In addition to the values of $pb/2V$ obtained with full available aileron control, the wing span, the wing loading, the pilot's opinion of the control effectiveness, and a sketch of the wing-aileron combination are included for each airplane. Except as indicated in the table, the maximum values of $pb/2V$ given were substantially constant over the speed range tested. Deviation from constant values in the very large airplane (airplane K) resulted from control-cable stretch that also limited aileron power even at low speeds. An average value of $pb/2V$ is given for this airplane. For the airplane U with retractable ailerons, the value given of $pb/2V$ is for low-speed flight.

CRITERION FOR AILERON EFFECTIVENESS

Comparison of the measured values of $pb/2V$ with pilots' opinions of the lateral-control effectiveness suggests a lower limit for the amount of lateral control that is considered satisfactory by pilots. Although the values of $pb/2V$ varied considerably among the various airplanes tested, no case was recorded where control was considered adequate for values of $pb/2V$ less than 0.07 or where inadequate control was reported for airplanes exceeding this limit. The same limit appears to apply to large airplanes as well as small airplanes regardless of wing loading or purpose for which the airplane was intended.

Values of $pb/2V$ much greater than the suggested lower limit of 0.07 were experienced in several cases. These airplanes were not considered by the pilots to be particularly outstanding or to be superior in essential qualities of control to airplanes developing much lower values. On the other hand, none of the ailerons tested were considered as being too effective.

The requirement for satisfactory lateral control indicated by the present analysis is at considerable variance with the criterion previously used by the NACA. Requiring that the maximum value of $pb/2V$ should never be less than 0.07 is the same as specifying that the maximum rolling-moment coefficient should not be less than $0.07C_{l_p}$, a value that is constant for any given airplane. On the other hand, the rolling criterion of references 1 and 2 specified that the ratio of rolling-moment coefficient to lift coefficient be a constant. The value of C_l/C_L that was suggested was 0.075 although, as stated in reference 2, a value possibly half as great might be used for airplanes not intended to be aerobatic.

The C_l/C_L criterion was designed primarily for application to the low-speed conditions for airplanes of the private-owner type. In the light of the present investigation it is considered ultraconservative for all types at low speeds. Comparison of the test results on airplanes of different wing loadings indicates that the rolling-moment coefficient required for satisfactory control is independent of lift coefficient. As the minimum speed and not the lift coefficient is apparent to the pilot, a heavily loaded airplane with a high-lift device should require no greater rolling-moment coefficient, and corresponding helix angle, than is required by a lightly loaded airplane of equivalent minimum speed.

As regards the variation of rolling-moment coefficient with lift coefficient implied by the C_l/C_L criterion throughout the speed range, the present analysis indicates that no such marked drop in aileron effectiveness can be tolerated with increased speed. Rather, it appears that a rolling-moment coefficient large enough to give the specified value of $pb/2V$ is desired and is used by pilots up to reasonably high speeds. For large airplanes this amount of control is required chiefly to

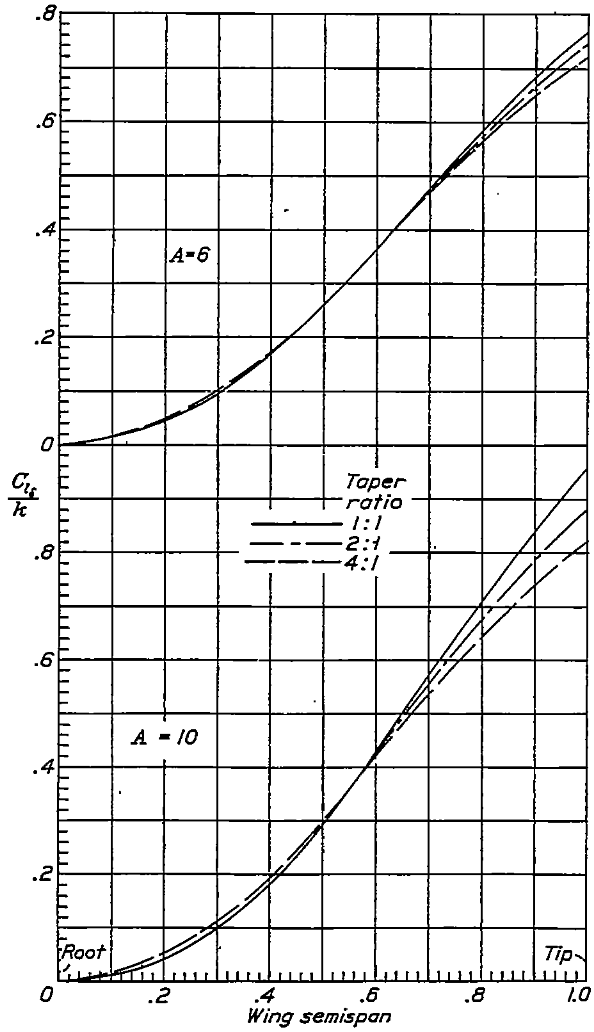

FIGURE 1.—Variation of C_{l_δ}/k with aileron span, aspect ratio, and taper ratio (from reference 3).

provide sufficient corrective control for rolling due to atmospheric disturbances. For airplanes of the pursuit category, this amount of control appears to be required in maneuvering at high speeds. In this connection, airplanes with high stick forces may have insufficient aileron control at high speeds because the controls cannot be deflected a sufficient amount.

The rolling requirements of pursuit types, in addition, call for consideration of the actual rolling velocities available, because the maneuverability in roll is dependent on the time required to bank the airplane at maneuvering speeds. As indicated, a value of $pb/2V$ of 0.07 appears to give adequate rolling velocities at maneuvering speeds for pursuit airplanes of the types tested because of the short span used and the relatively high maneuvering speeds. The use of greater wing spans in airplanes of this type would, of course, require proportionately larger values of $pb/2V$ unless a reduction of maneuverability in roll could be accepted.

For ailerons of the conventional trailing-edge type, the criterion as expressed in terms of $pb/2V$ is sufficient to insure satisfactory aileron effectiveness. For lateral controls that depend on spoiler action, however, unsatisfactory characteristics may result from lag or from an incorrect initial response even though the specified value of $pb/2V$ is obtained. Some of the difficulties experienced with spoilers are discussed in reference 2.

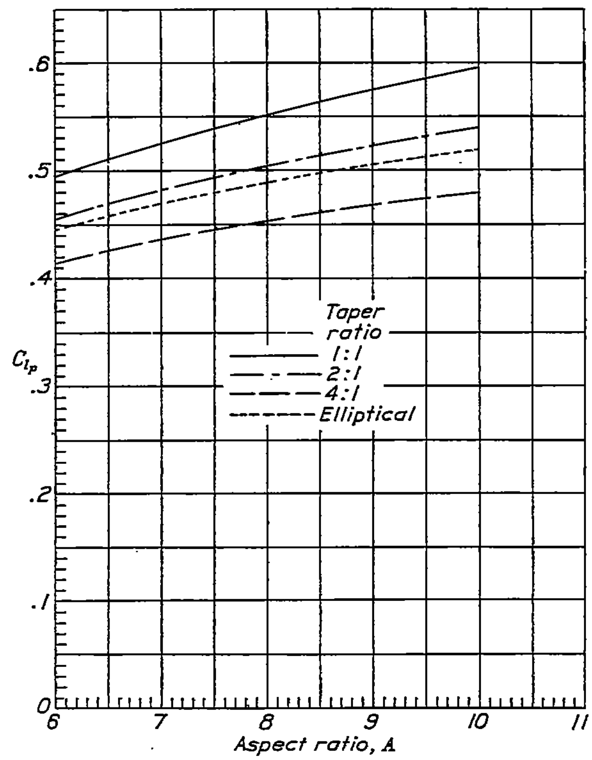

FIGURE 2.—Variation of C_{l_p} with aspect ratio and taper ratio (from reference 3).

PREDICTION OF AILERON EFFECTIVENESS

In the analysis of flight results, an attempt was made to develop a simple expression that would correlate the observed data and allow prediction of aileron effectiveness for future designs. By the adaptation of the theory of reference 3 to the present investigation, the effectiveness of a given aileron installation was expressed as follows:

$$\frac{pb}{2V}=\left(\frac{C_{l_\delta}}{k}\right)\frac{(k)(\Delta\delta_a)}{(114.6)(C_{l_p})} \qquad (1)$$

Curves for determining the value of C_{l_δ}/k and of C_{l_p} for a given airplane were taken directly from reference 3 and are reproduced as figures 1 and 2. Direct interpolation, although not strictly correct, may be used to determine C_{l_δ}/k with sufficient accuracy in practical work for airplanes of aspect ratios other than those given in figure 1. In use, the value of C_{l_δ}/k is read at a point on the semispan corresponding to the position of the outer end of the aileron, and from this value is deducted the value read at a point corresponding to the inner end of the aileron. The quantity thus obtained is the value of C_{l_δ}/k used in the formula. The coefficient C_{l_p}, of course, does not vary with aileron span.

The values of the aileron effectiveness factor k, when $\Delta\delta_a=30°$, were determined from the observed $pb/2V$ values of the various airplanes tested in flight and are presented in figure 3 as a function of the ratio of mean aileron chord $\bar{c}_a$ to mean wing chord $\bar{c}_{w_a}$. The values figure 3 should give sufficiently conservative results.

In general, the aileron effectiveness factor k for plain ailerons did not vary with aileron deflection for angles up to approximately ±20°. With the balanced ailerons, however, the effectiveness factor was a maximum at small deflections and usually decreased progressively as the deflection increased so that the values given in figure 3 should be somewhat reduced if a deflection range greater than 30° is contemplated.

CONCLUDING REMARKS

The helix angle $pb/2V$ generated by the wing tip of an airplane in an abrupt aileron roll appears to represent the aileron control effectiveness appreciated by pilots. The lower limit for satisfactory aileron effec-

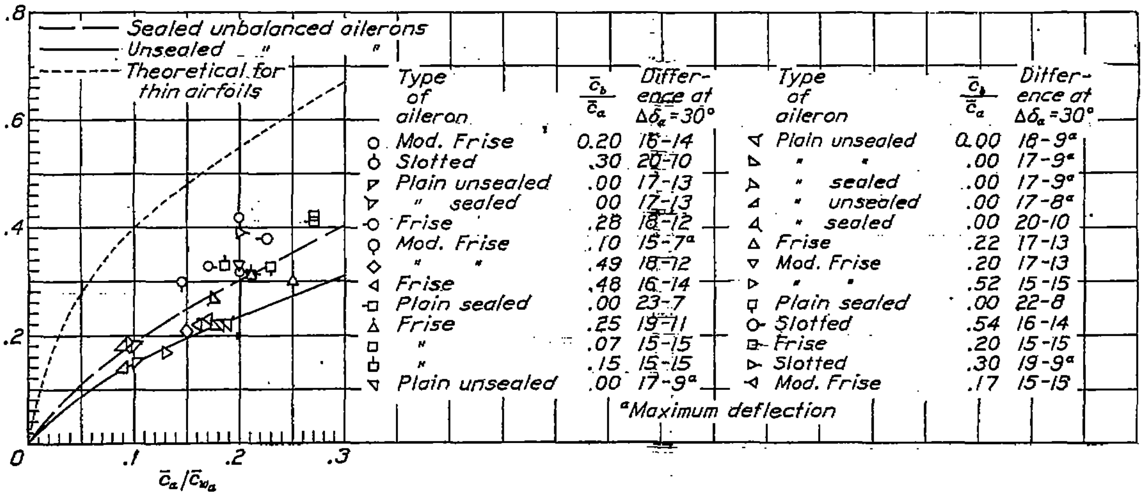

FIGURE 3.—Aileron effectiveness factor k, as measured in flight for various wing-aileron arrangements ($\Delta\delta_a=30°$).

of k determined in flight are considerably lower than those predicted by theory and, in most cases, they are lower than values obtained for comparable aerodynamic arrangements in the wind tunnel. At least part of this effect may be accounted for on the basis of the deflection of the wing in torsion and the deflection of the aileron control system. For example, 1° of wing twist varying uniformly from the wing tip would reduce the apparent aileron effectiveness by about 20 percent. The wing deflections experienced by the various airplanes, however, are unknown. The deflections that occurred between the ailerons and the cockpit control are likewise unknown. Inasmuch as aileron deflections were determined on the basis of the position of the cockpit control, this fact would further tend to reduce the apparent aileron effectiveness. For these reasons, it would seem unwise to draw any final conclusions regarding the relative merits of the aileron types employed.

If the rigidity of the wing and the control system is known, accurate prediction of aileron effectiveness should be possible on the basis of wind-tunnel data for the aileron type employed. If this information is lacking, however, the curves for plain ailerons given in

tiveness expressed in this form, that is, $pb/2V=0.07$, was independent of the size or category of the airplane tested.

Study of the observed values of $pb/2V$ for the various wing-aileron arrangements tested indicated that the aileron effectiveness developed in flight may be considerably less than that theoretically predicted on the basis of aileron characteristics measured in the wind tunnel, presumably because of wing twisting and deflections in the aileron-control system. In aileron design, therefore, the rigidity of the wing in torsion and the rigidity of the control system must be considered as well as the aerodynamic properties of the wing-aileron combination. In addition, secondary rolling moments due to aileron yaw may have an important influence on aileron control, particularly at low speeds. Ailerons otherwise satisfactory may appear defective when the directional stability of the airplane is too low to restrict the aileron yaw to reasonably small values or when the dihedral effect of the wing is such that the effects of yaw on the rolling moments are accentuated.

Although this report is not primarily concerned with aileron control forces, several of the airplanes tested were unsatisfactory in this respect. In some cases, however, material reduction in stick force has been possible simply by a restriction of the deflection range of the ailerons to that required. The maximum stick force varies as the square of the deflection range, because mechanical advantage of the control system as well as the hinge moments of the ailerons is involved.

The point previously made regarding aileron control at the stall may well be emphasized again. Aileron control here depended upon the symmetry of flow and the rate at which the flow broke down on the wing and had no correlation with the control available in normal flight. In no case was aileron control retained when the wing was completely stalled; roll against the ailerons usually occurred as a result of the adverse yaw developed.

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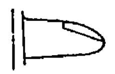
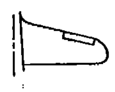
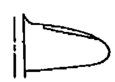
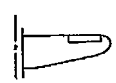
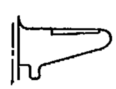
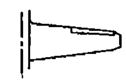
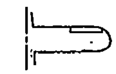
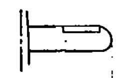
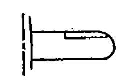
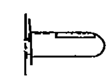
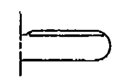
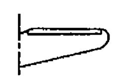
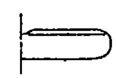
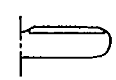
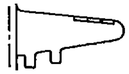
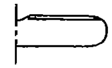
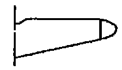
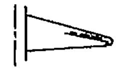
National Advisory Committee for Aeronautics,
Langley Field, Va., *April 18, 1941*.

REFERENCES

1. Weick, Fred E., and Wenzinger, Carl J.: Wind-Tunnel Research Comparing Lateral Control Devices, Particularly at High Angles of Attack. I—Ordinary Ailerons on Rectangular Wings. Rep. No. 419, NACA, 1932.
2. Weick, Fred E., and Jones, Robert T.: Résumé and Analysis of N. A. C. A. Lateral Control Research. Rep. No. 605, NACA, 1937.
3. Pearson, Henry A., and Jones, Robert T.: Theoretical Stability and Control Characteristics of Wings with Various Amounts of Taper and Twist. Rep. No. 635, NACA, 1938.

TABLE I.—CHARACTERISTICS OF AIRPLANES TESTED

Airplane	Type	Wing-aileron arrangement	Type of control	Span (ft)	Wing loading (lb/sq ft)	$\left(\frac{pb}{2V}\right)_{max}$	Satisfactory in pilot's opinion?
A	Pursuit		Modified Frise balanced	36.0	27.2	0.105	Yes
B	Pursuit		Slotted	36.0	29.0	.086 (approx.)	Yes
C	Pursuit		Slotted	37.3	23.9	.100	Yes
D	Pursuit		Slotted	37.3	27.0	.081	Yes
E-1	Pursuit		Plain unbalanced unsealed	30.0	19.3	.075	Yes
E-2	Pursuit		Plain unbalanced sealed	30.0	19.3	.083	Yes
F	Trainer		Frise balanced	42.0	19.7	.088	Yes
G	Scout bomber		Modified Frise balanced	42.0	20.3	.072	Yes
H	Bomber		Modified Frise balanced	70.5	20.0	.126	Yes
I	Bomber		Modified Frise balanced	89.6	22.4	.081	Yes
N	4- or 5-place commercial		Frise balanced	41.8	14.7	0.096	Yes
O	3-place commercial		Modified Frise balanced	34.2	9.4	.076	Yes
P	3-place commercial		Frise balanced	34.0	9.7	.089	Yes
Q	2-place commercial		Frise balanced	36.0	6.8	.147	Yes
R	2-place commercial		Frise balanced	36.0	6.1	.103	Yes
S	2-place commercial		Frise balanced	35.2	5.5	.098	Yes
T-1	Experimental		Plain unbalanced unsealed	32.8	10.1	.075	Yes
T-2	Experimental		Plain unbalanced unsealed	32.8	8.8	.082	Yes
T-3	Experimental		Plain unbalanced unsealed	32.8	10.1	.071	Yes
T-4	Experimental		Plain unbalanced sealed	32.8	10.1	.088	Yes

J	Bomber		Modified Frise balanced	104.0	27.1	.046	No	T-5	Experimental		Plain unbalanced unsealed	32.8	10.1	.019	No
K	Bomber		Frise balanced	149.0	17.6	.039 (average)	No	T-6	Experimental		Plain unbalanced sealed	32.8	10.1	.071	Yes
L	Transport		Plain unbalanced sealed	49.5	24.7	.071	Yes	T-7	Experimental		Floating wing tip	35.8	8.6	.055	No
M	Transport		Plain unbalanced sealed	65.6	27.5	.086	Yes	U	Experimental		Retractable	34.0	15.1	.047 (low speed)	No